Smart Grid Conference (SGC 2015)
23-24 Dec. 2015, Iran University of Science and Technology, Tehran, Iran

Intelligent Over-Current Protection Scheme in Inverter-based Microgrids

Rahmat Khezri*, Shoresh Shokoohi*, Sajjad Golshannavaz**, and Hassan Bevrani*
* Department of Electrical and Computer Engineering, University of Kurdistan, Kurdistan, Iran,
r.khezri.2014@ieee.org
** Electrical Engineering Department, Urmia University, Urmia, Iran

Abstract: *Recently by technological developments in inverter-based devices, application of these prominent apparatus has gained more attention in newly emerged microgrids (MGs). In this paradigm, the concept of multiple inverter-interfaced distributed generations (IIDGs)-based MG is now a reputable term. According to fast dynamic responses of IIDGs, study of their transient behaviors seems essential. Among the important indices of IIDG-based MGs in transient situations, the current index is the most susceptible one, which should not be higher than twice values of rated current due to their physical constraints. This paper proposes a proportional-integral (PI) controller adjoined in the voltage source inverter control loop to well-protect the IIDGs against the possible over currents during short circuit faults in MG. To adapt the PI controller for both connected and autonomous modes and different short circuit faults in MG, fuzzy logic as an intelligent method is employed to fine-tune of the PI gains. The obtained results illustrate the efficiency of fuzzy-based fine tuning approach.*

Keywords: Inverter-based microgrids, inverter interfaced distributed generations, transient stability, transient PI control loop, fuzzy-based fine tuning.

1. Introduction

Configuration of future power systems will be changed by considerable engagement of distributed generators (DGs). Collection of DGs with domestic loads and other distributed resources (DRs) such as distributed storage systems has established a new concept called as microgrid (MG) [1]. MGs have some potential benefits such as increasing the grid efficiency, high electricity reliability to supply the consumers, generating power closer to electrical loads, satisfying environmental issues due to utilization of renewable resources. As well, a MG can operate in both grid-connected and stand-alone modes. Nonetheless, challenges due to use of power electronic devices, increasing voltage and frequency fluctuations, changing of power flow patterns and stability criterions serve as the MGs problems which have been concerned over the recent years [2].

Due to swift and vast deployment of DGs based on power electronics devices, it is so vital to investigate their control performance in the MGs. The majority of employed inverter-interfaced DGs (IIDGs) in MGs are based on the voltage source inverter (VSI) topology which is operating with sufficient closed loop control. According to new structures and various operation modes in MGs, the control topology of DGs has attracted more attentions [3-8]. The significance of voltage and frequency performance of inverter-based MGs is well-assessed in literature [4-6]. According to application of VSI-based DGs with specific local droop characteristic in MGs, a generalized droop control (GDC) scheme for a wide range of load changes is designed in [4]. Optimal tuning of the GDC parameters in this work has been targeted by [5] using fuzzy method to obtain the best voltage and frequency performance of the IIDGs. The improved voltage and frequency control does enhance the quality of power supplied by the DG unit connected to the MG. This aim is satisfied by a designed power controller in [6] which utilizes particle swarm optimization (PSO) approach as a self-tuning method in order to regulate the voltage and frequency in transient situations. Combination between fuzzy logic and PSO approach is introduced in [7] for online tuning of the proportional-integral (PI) based frequency controllers devised for AC MG systems. To optimal retrieval of frequency, $H\infty$ and μ-synthesis robust control techniques are used to develop the secondary frequency control loop in [8].

Stability concept as an important issue for power systems is of high concern in MGs according to extended application of IIDGs in these advanced systems [9, 10]. On the other hand, the need to reliable operation of MGs forced the researchers to investigate the stability issue in inverter-based MGs more significantly. In this context, dynamic stability of a typical MG is analyzed based on small-signal model in [11]. Consequently, a relationship between dynamic stability, operation state, and the MG configuration is obtained by small-signal model and eigenvalues analysis of the MG. It is illustrated in [12] that the stability margins of an inverter-based MG for different droop control gains can be accurately determined by transforming each inverter into an equivalent network. A hybrid MG with induction motor loads may lose its stability in fault-forced islanding situations even if the fault is isolated within a typical clearing time [13]. The small-signal stability of an inverter-based MG is enhanced by utilizing an arctan function for power-frequency droop control in conventional IIDGs [14]. Design of new adaptive decentralized droop controller to prevent power sharing stability in MGs is demonstrated in [15]. The power sharing stability is attributed by drifting the low-frequency modes of power sharing dynamics to new locations following the changes in the demanded power of each IIDG. A nonlinear MG stabilizer is introduced by [16] to guarantee the stability and reliable performance of MGs during severe faults and transients such as islanding and large load changes.

As noted, the literature shows distinctive stability concepts for inverter-based MGs, but the substantial stability concept as referred by transient stability is not mentioned accurately by the researchers, which is the main concern of ongoing study. Among the important indices of inverter-based MGs in transient situations, the current index is the most susceptible one, which should not be higher than twice values of rated current due to their physical constraints [17]. As a practical remedy in preventing large overshoots in response to transient currents in IIDGs, an instantaneous over-current shutdown protection is added to these systems [18]. Also, it is illustrated that the developed fast response time of IIDGs makes it necessary to consider their fault current contributions during sub-transient period as well as transient period. To overcome the shutdown obstacle in IIDG systems, a new transient over-current control loop (TOCL) based on PI-controller is added to the VSI control strategy of IIDGs in this paper. The proposed TOCL is able to protect IIDGs from over-currents which may occur outside the MG network. However, facing with three-phase faults in autonomous mode of MG and inside its territory, the TOCL cannot protect the IIDGs from over-currents. According to the raised discussions, the gains of PI-controller in TOCL structure should be modified for adaptation. In this way, the main focus of current paper is to design and then numerical validation of a fuzzy logic-based fine tuning (FLFT) approach intended to enhance the over-current protection in first swing of inverter-based MGs. The founded FLFT approach is included for judicial parametrical tuning of PI controller encountering fault occurrences in autonomous mode of MG.

The remainder of this paper is organized as follows. Section 2 reviews the inverter-based MGs and over-current issue in these networks. In section 3, the GDC control structure of IIDGs and proposed TOCL will be discussed. Afterwards, section 4 undertakes the design procedure of the proposed FLFT approach for efficient over-current protection facing with three-phase faults in autonomous state of MGs. As the ending point, section 6 concludes the paper.

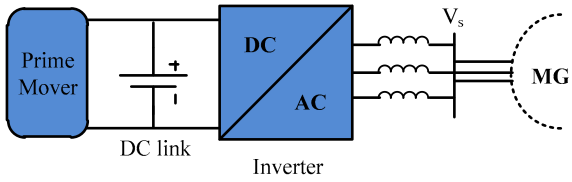

Fig. 1: An IIDG scheme

2. Inverter-based MGs and Over-Current Issues

2.1 IIDGs configuration

There are two basic classes of distributed energy resources (DERs). One includes the DC energy resources such as fuel cells and photovoltaics and the other is high frequency AC resources such as micro-turbine, which needs to be rectified. In both cases, the result of DC voltage is converted to an acceptable AC source using an inverter. Therefore, a power electronics interface is necessary to convert DC voltages into an AC one [19]. These types of DERs which are connected to MG by means of inverters are named inverter-interfaced DGs (IIDGs). The general schematic of an IIDG is shown in Fig 1. An IIDG is composed of prime mover, DC interface, and DC to AC converter. The prime mover can be a fuel cell, a photovoltaic cell, or a rectified output of high frequency DERs. Due to fluctuating nature of DERs, the DC output voltage is not completely fixed. Thus, a storage system is used between the prime mover and the inverter. The task of the storage devices is based on the equilibrium between generation and consumption. In fact, storage devices play the same task of spinning reserve in traditional power systems. Due to existence of the power storage interface during transients, the prime mover dynamics can be ignored [18].

2.2Over-Current Protection in inverter-based MGs

The most important advantage of IIDGs is their quick response against the changes in the output. If a change happens in the MG, the IIDGs can compensate it quickly. But, this fast response to probable changes is characterized with some negative effects on the fault current [20]. During an event, the IIDG response depends basically on the inverter control structure [18]. To prevent damaging of switching devices adjoined in the inverter, IIDGs are equipped by instantaneous over-current shutdown protection. This is necessary to prevent damage to the semiconductor devices used in the IIDGs. If dangerous over-currents impress the switching devices for more than several microseconds, the over-current protection activates and decreases the output current to zero in less than a millisecond [20]. The results approve that the voltage falls significantly in the first cycle following the fault and then reaches a constant value. Meanwhile; the fault current increases rapidly. Due to slight changes in power during a fault, the VSI controller cannot affect the fault current peak during sub-transient period (first cycle) and transient period (between third

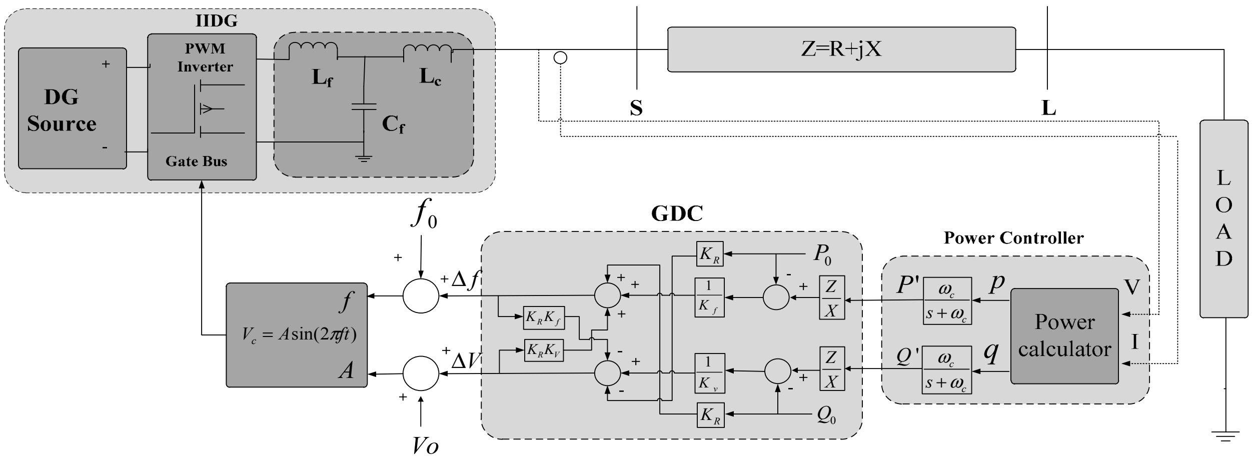

Fig. 2: Generalized droop control structure of IIDG

and 10-*th* cycles) [18]. The only constraint which leads to the instability of IIDGs is passing fault current more than maximum tolerable power in its switching devices. In practice, instantaneous over-current protection is designed so that if current reaches to the twice values of current nominal value, the VSI would be failed [21]. This over-current value can be calculated by (1).

$$I_{oc} = 2I_n = 2\frac{S_n}{\sqrt{3}U_n} \quad (1)$$

po… omplex … case of voltage control process, the short-circuit currents of IIDGs which is mostly determined by the network configuration can be defined as an index to evaluate MG's transient stability. Therefore, if I_{oc} is smaller than its predefined maximum value, then IIDG is transiently stable. Otherwise, IIDG should be tripped off by relay protection leading to MG collapse without any power supply.

3. Control Structure of IIDG

3.1. Generalized droop control (GDC)

The droop control loops in IIDGs should compensate voltage and frequency deviations such that acceptable

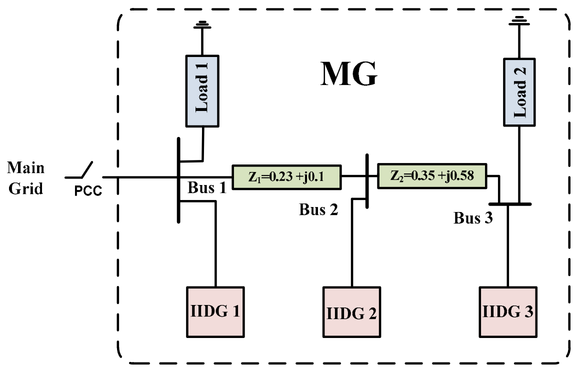

Fig. 3: MG with three IIDGs

values are anticipated to be obtained for these components following disturbances. A load change in a MG may lead to imbalances between generation and consumption which it could change the output voltage and frequency of the VSIs due to the droop characteristics. If the load change is sensibly large, the IIDGs may be unable to stabilize the MG. For this purpose, efficient droop control loops should be selected for IIDGs. A generalized droop control (GDC) structure based on line parameters is presented in [4]. This GDC is proposed based on the well-known conventional voltage/frequency droops. The GDC structure is illustrated in Fig. 2. In this structure, the active and reactive powers are simultaneously deployed to compensate the voltage and frequency droops after any change in load. In Fig. 2, K_f and K_V are droop coefficients and K_R is an index to demonstrate what percentage of line is resistive. The GDC presents a more real model for droop control in IIDGs. Due to averaging in calculating active and reactive powers of the inveter (P and Q), it is expected that the GDC cannot restrict the output current of IIDG in fault durations. Let suppose that the MG is connected to the main grid at the fault time period.

To evaluate the performance of GDC in transients, a MG including three units of inverter (Fig. 3) is selected as the test bed. The IIDGs (220 V, 50 Hz) are connected to two local load banks determined at bus 1 and bus 3.

System parameters are given in [4]. Also, it is considered that the MG is connected to the IEEE 37-bus test feeder [22] in the node 775 (Fig. 4). To analyze the transient current behavior of the GDC, the first cycle of the output current of the IIDGs should be studied during faults in the distribution system. In connected mode, the voltage amplitude and frequency of the node 775 with the nominal values of 220 V and 50 Hz respectively are selected as the reference value [23]. In order to check the performance of the GDC in transients, the bypass switch located between node 775 and MG will stay connected during fault. As well, fault will not be removed. At t=0.5s, a three phase fault is occurred at node 703. The output currents of IIDGs are illustrated in Fig. 5. As it is shown, the output currents

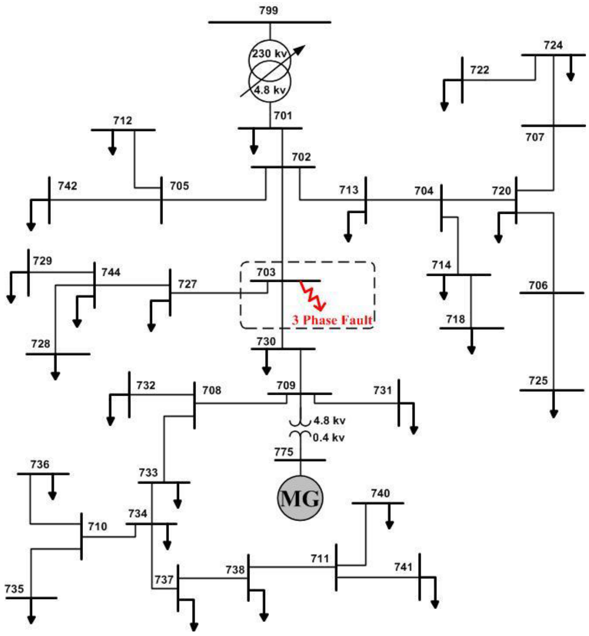

Fig.4. IEE 37-bus test feeder with MG

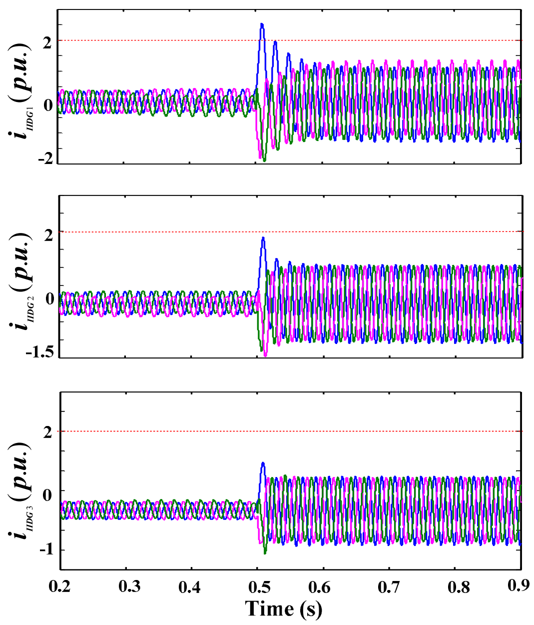

Fig. 5: Output currents of IIDGs with simple GDC

of IIDG1 and IIDG2 exceed from twice nominal value at the first cycle (subtransient period). But, due to more distance from node 775, the output current of IIDG 3 does not exceed from its critical limit (twice nominal current of each IIDG). This scenario reveals that the GDC structure is not efficient during fault and before disconnecting bypass switch. This observation is due to activation of instantaneous protection system of inverter where IIDG1 and IIDG2 are failed in less than a few milliseconds. Therefore, the MG will collapse after disconnecting the interfacing bypass switch (islanded mode). It is certified that GDC needs an extra loop for current control in transients.

3.2 Over-Current Protection Control Loop

During fault conditions, violent current deviations occur at sub-transient periods. Thus, if these deviations are suitably converted to corresponding voltage deviations through a PI controller and then supplemented to the voltage droop control, the speed of GDC response can be increased. The transient control loop should be designed in such a way that it does not affect the IIDGs output in the steady-states. As well, it should be apt to decrease the output current of IIDGs at the sub-transient periods. In this way, the proposed transient loop is shown in Fig. 6. In this configuration, the output current derivative is to be sampled as the initial task. Then, in order to diminish the current deviations toward zero values; the root mean square (RMS) values of output current derivative is supplemented to the voltage droop control loop. For this scenario, the gains of PI controller are tuned based on trial and error approach, say as K_P = 0.004 and K_I = -0.01.

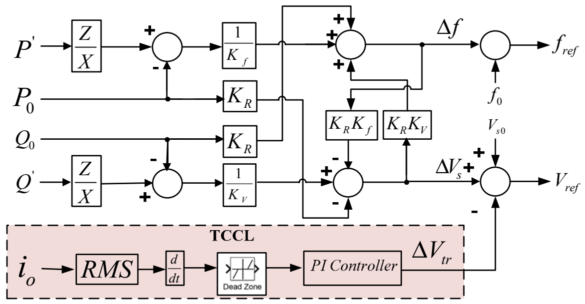

Fig. 6: Transient over-current loop in GDC

As it is illustrated in Fig. 7, by deploying the PI-based TOCL, IIDGs output currents peak values are decreased during subtransient/transient state. Due to proper performance of the TOCL, none of IIDGs is failed. Therefore, the MG can stably supply local loads in the isolated mode whenever the bypass switch triggers.

As it has been mentioned earlier, dynamic performance of MGs in connected and autonomous states is quite distinct. Regarding high inertia of main systems, in connected mode MGs have slower dynamics; however, in autonomous mode with regards to low inertia of IIDGs, the MGs have faster dynamics and there is no enough time to adaptation of TOCL in this mode. Considering this issue, another scenario is simulated for the examined MG in disconnected mode. In this scenario, after the three phase fault in node 703, the bypass switch located between node 775 and MG is disconnected at t=0.55s; meanwhile in autonomous state a three phase fault is occurred in the bus 2 of MG at t=7s. Fig. 8 illustrates the performance of simple TOCL in this scenario. As it is shown, with respect to distinctive dynamics of the MG in connected and disconnected modes, the TOCL is unable to stabilize the MG and hence the IIDG2 is failed. Therefore, the gain values of PI controller in TOCL structure should be adapted for different situations with distinctive dynamics.

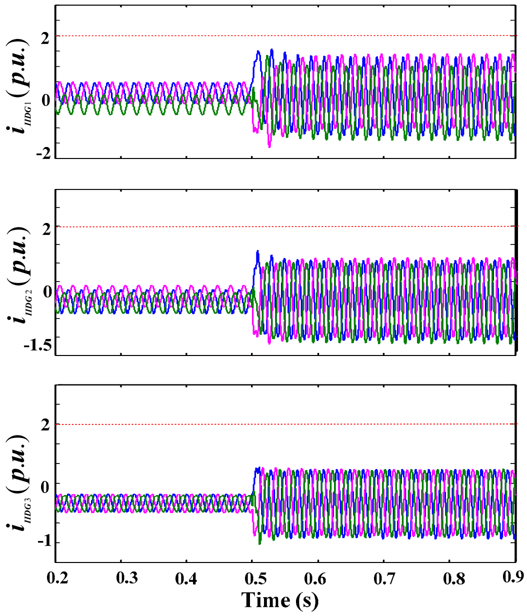

Fig. 7: Output currents of IIDGs with TOCL

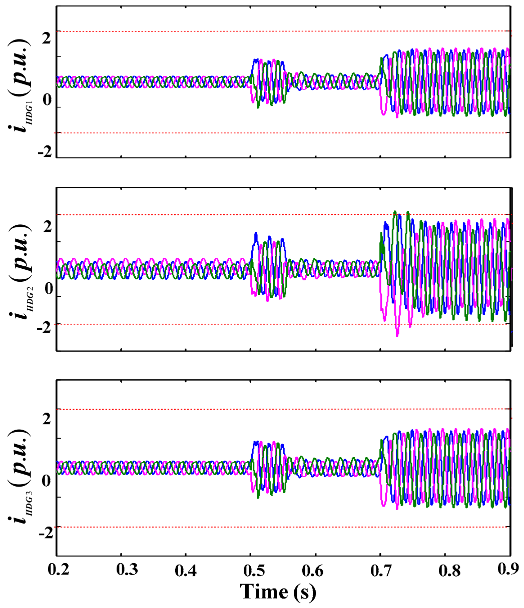

Fig. 8: Output currents with TOCL (fault in bus 2)

4. Fuzzy-based Fine Tuner

Fuzzy logic approach is well-defined as an artificial method capable of handling complex and non-linear engineering processes where the classical control theory becomes rather ineffective. In recent decades, there has been a great transition among the researchers to make benefit of fuzzy logic technique in handling the control requirements of modern power systems. This trend, introduced by Lotfi-Zadeh in 1965 [24], has been provoked due to its independency against the nonlinearity, complexity, and mathematical model extraction of the test system. Hence, nourished through a knowledge-based nature, the fuzzy logic approach is able to rehabilitate the shortcomings of conventional PI controllers in obtaining the optimal performance in various conditions of MGs. Inspired by these marvelous features, fuzzy logic technique has been preferred herein as the investigated control platform. Following the investigated theme, this section aims to present the design procedure of FLFT approach for effective over-current decay in IIDGs. Designing controllers based on the fuzzy approach for dynamic systems need following steps [25]:

- Grasping of the system dynamic behavior characteristics. Define the states and input/output control variables and their variation ranges.
- Identify sufficient fuzzy sets and membership functions. Create the degree of fuzzy membership function for each input/output variable and complete fuzzification.
- Determine a suitable inference engine. Construct the fuzzy rule base using the control rules that the system will operate under. Decide how the action will be executed by assigning signsl strengths to the rules.
- Assess defuzzification method. Incorporate the rules and defuzzify the output.

Therefore, a fuzzy system is composed of four main sections: fuzzification, fuzzy rule base, inference system and deffuzzification. The proposed control framework for application of fuzzy controller in this paper has two inputs and two outputs. The RMS quantity of output current of IIDG and its derivative are selected as input signals for the fuzzy tuner. The output signals are suitably adjoined to the conventional PI controller as virtual gains encountering fault situations. Thus, in steady-state conditions, the effect of FLFT-controller is excluded and the conventional PI controller performs as a safe controller in industry works solitude. In other words, the main function of FLFT controller is to retune the conventional PI gain values encountering disturbances while letting pass the steady state conditions with no change. In this viewpoint, the FLFT controller represents a fine-tuning system supplemented to the conventional PI controller. The structure of the designed FLFT-based controller is demonstrated in Fig. 9.

As it is seen, this controller modifies the PI controller parameters, namely K_p and K_i, to obtain the best performance. In this paper, in order to reach a fast

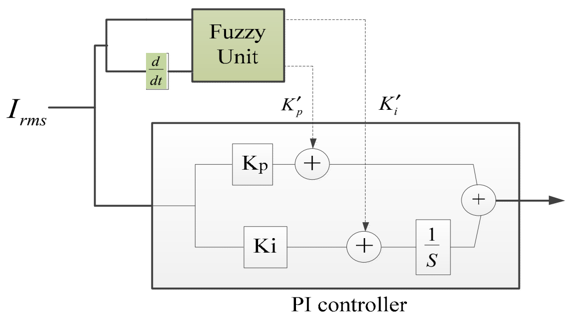

Fig. 9: Fuzzy-based fine tuner added to conventional PI

response from the controller loop, all membership functions are considered as triangular with the mathematical definitions as follows:

$$\mu_x(x_i) = \max\left(0.1 - \left|\frac{x - x_i}{c}\right|\right) \tag{2}$$

Where x and c are the mean and spread of the fuzzy set X, respectively and x_i is a crisp variable. Herein, the membership functions corresponding to the input variables are arranged as Negative (N), Zero (Z), and Positive (P). As well, the membership functions for the output variables are arranged as Negative Large (NL), Negative Small (NS), Zero (Z), Positive small (PS), and Positive Large (PL). In the present investigation, three membership functions are defined for the input signals and five membership functions are defined for the outputs. The membership functions for input and output variables are demonstrated in Fig. 10.

The Mamdani inference system is also used for the proposed fuzzy controller. The fuzzy rules configurations for the proposed controller are as follows:

IF I_{rms} is N AND dI_{rms} is N, THEN output is PL.
IF I_{rms} is N AND dI_{rms} is Z, THEN output is PS.
IF I_{rms} is N AND dI_{rms} is P, THEN output is PL.
IF I_{rms} is Z AND dI_{rms} is N, THEN output is PS.
IF I_{rms} is Z AND dI_{rms} is Z, THEN output is Z.
IF I_{rms} is Z AND dI_{rms} is P, THEN output is NS.
IF I_{rms} is P AND dI_{rms} is N, THEN output is PS.
IF I_{rms} is P AND dI_{rms} is Z, THEN output is NS.
IF I_{rms} is P AND dI_{rms} is P, THEN output is NL.

As it can be seen, in the above IF-THEN statements, the antecedent part of the rules is composed of two parts which are combined with fuzzy "AND" operator. In this paper, the combination is done based on interpreting the "AND" operator by algebraic product operation. Following the inference engine, defuzzification converts the output fuzzy values to their corresponding crisp values based on appropriate membership functions analogous to the fuzzification stage. As the last step, the defuzzification process is commonly tackled based on center of gravity, mean max, and weighted average methods to defuzzify the fuzzy control law. Here, the center of gravity method is employed for defuzzification task [7]. To illustrate the efficiency of designed FLFT, two scenarios are simulated. At the first scenario, after the three phase fault at node 703, the bypass switch located between node 775 and MG is disconnected at t=0.55s; meanwhile in autonomous state a three phase fault is occurred at bus 2 and t=7s. This scenario is same as the previous scenario in section 5. Fig. 11 illustrates the performance of FLFT with conventional PI controller in this scenario. As it is seen, compared to the previously designed controller (TOCL) with simple PI controller, accommodating the proposed FLFT approach in over-current protection task has evidently diminished the over-currents and prevented the MG from being unstable; so, none of IIDGs is failed.

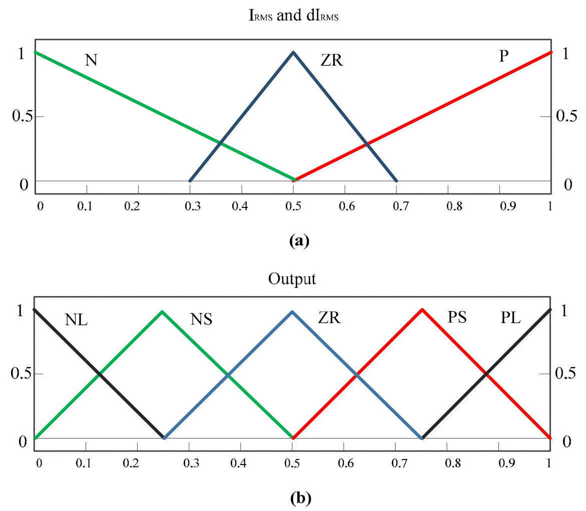

Fig. 10: Membership functions for inputs and outputs

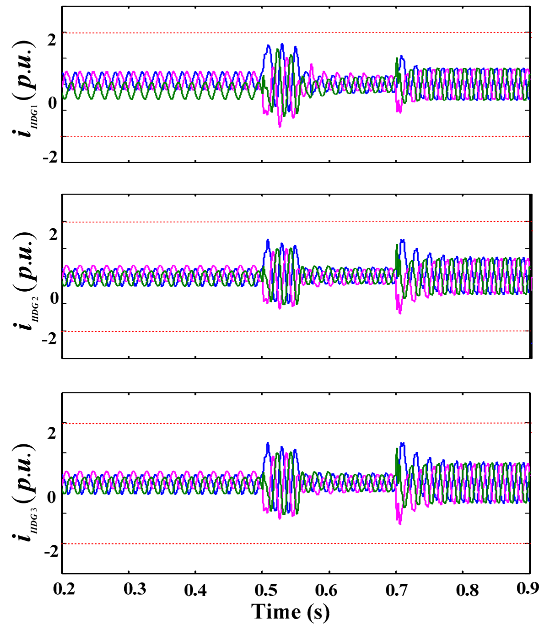

Fig. 11: Output currents after adding FFT in first scenario

As the second scenario in this section, after disconnecting the MG a three phase fault at bus 1 occurs at t=7s. As it can be observed from Fig. 12, by deploying FLFT approach rather than PI-based TOCL, the IIDGs output current peak values are not exceeded from twice nominal value of current during subtransient/transient states. Due to proper performance of the FLFT, none of IIDGs is failed. Therefore, the MG can stably supply local loads in isolated mode whenever the bypass switch acts.

5. Conclusion

Recent MGs are structured based on inverters, so that IIDGs organize the main distributed resources of them. According to fast dynamic responses of IIDGs, study of their transient behaviors seems essential. Among the important indices of IIDG-based MGs in transient situations, the current index is the most susceptible one,

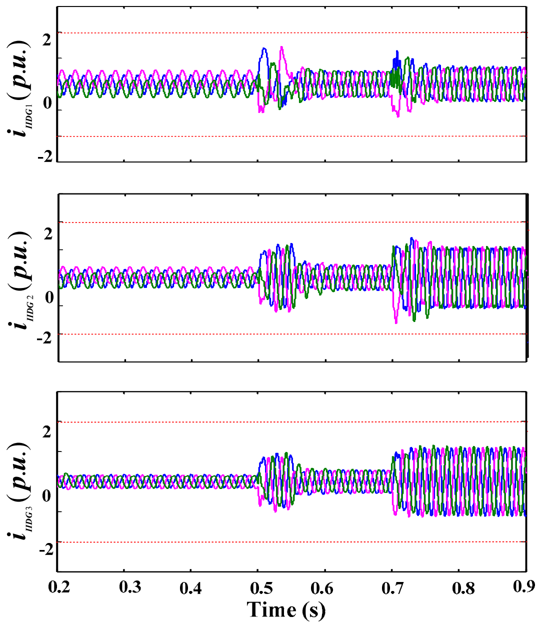

Fig. 12: Output currents after adding FFT in second scenario

which should not be higher than twice rated due to their physical constraints. The followings could be deduced as the remarkable observations of the paper:

- It is demonstrated that, the simple GDC is extremely vulnerable against transient currents.
- By addition of transient over-current control loop based-on PI controller to the structure of GDC, transient currents of IIDGs in connected mode are reduced to acceptable ranges. But, this loop is unable to sufficient protection of IIDGs against transient currents in autonomous mode of MGs.
- A fuzzy-based fine tuner by two inputs and two outputs is introduced for optimal gain tuning of PI controller in autonomous mode of the MG. The proposed method reduced transient currents to sufficient ranges in such condition.

References

[1] H. Bevrani, M. Watanabe, and Y. Mitani, "Microgrid controls," in Standard Handbook for Electrical Engineers. New York, NY, USA: McGraw-Hill, 2012.
[2] H. Bevrani, M. Watanabe, and Y. Mitani, Power System Monitoring and Control. Hoboken, NJ, USA: Wiley, Jun. 2014.
[3] J. A. Pecas Lopes, C. L. Moreira, and A. G. Madureira, "Defining control strategies for microgrids islanded operation," IEEE Trans. Power Syst., vol. 21, no. 2, pp. 916- 924, May 2006.
[4] H. Bevrani, and S. Shokoohi, "An intelligent droop control for simultaneous voltage and frequency regulation in islanded microgrids," IEEE Trans. Smart Grid, vol. 4, no.3, pp. 1505- 1513, Sep. 2013.
[5] S. Ahmadi, S. Shokoohi, and H. Bevrani, "A fuzzy logic-based droop control for simultaneous voltage and frequency regulation in an AC microgrid," Int. J. Elect. Power Energy Syst., vol. 64, no. 15, pp. 148-155, 2014.
[6] W. Al-Saedi, S. W. Lachiwicz., D. Habibi, and O. Bass, "Voltage and frequency regulation based DG unit in an autonomous microgrid operation using particle swarm optimization," Int. J. Elect. Power Energy Syst., vol. 53, no. 4, pp. 742- 751, 2013.
[7] H. Bevrani, F. Habibi, P. Babahajyani, M. Watanabe, and Y. Mitani, "Intelligent frequency control in an AC microgrid: Online PSO-based fuzzy tuning approach," IEEE Trans. Smart Grid, vol. 3, no. 4, pp. 1935–1944, Dec. 2012.
[8] H. Bevrani, M. R. Feizi, and S. Ataee, "Robust Frequency Control in an Islanded Microgrid: H∞ and μ-Synthesis Approaches," IEEE Trans. Smart Grids, pp. 1- 12, July 2015.
[9] R. Majumder, "Some aspects of stability in microgrids," IEEE Trans. Power Syst., vol. 28, issue 3, pp. 3243 – 3252, Aug. 2013.
[10] N. Pogaku, M. Prodanovic, and T. C. Green, "Modeling, analysis and testing of autonomous operation of an inverter-based microgrid," IEEE Trans. Power Elect., vol. 22. No. 2, March 2007.
[11] X. Tang, W. Deng, and Z. Qi, "Investigation of the dynamic stability of microgrid," IEEE Trans. Power Syst., vol. 29, issue 2, pp. 698- 702, Nov. 2013.
[12] S. V. Iyer, M. N. Belur, and M. C. Chandorkar, "A generalized computational method to determine stability of a multi-inverter microgrid," IEEE Trans. Power Elect., vol. 25, no. 9, pp. 2420-2432, Sep. 2010.
[13] A. H. Kasem Alaboudy, H. H. Zeineldin, and J. L. Kirtley, "Microgrid stability characterization subsequent to fault-triggered islanding incidents," IEEE Trans. Power Delivery, vol. 27, no. 2, pp. 658-669, April, 2012.
[14] C. N. Rowe, T. J. Summers, R. E. Betz, D. J. Cornforth, and T. G. Moore, "Arctan power-frequency droop for improved microgrid stability," IEEE Trans. Power Elect., vol. 28, no. 8, pp. 3747-3759, Aug. 2013.
[15] Y. I. Mohamed, and E. F. El-Saadany, "Adaptive decentralized droop controller to preserve power sharing stability of paralleled inverters in distributed generation microgrids," IEEE Trans Power Elect., vol. 23, no. 6, pp. 2806- 2816, Nov. 2008.
[16] S. M. Ashabani, and Y. I. Mohamed, "A flexible control strategy for grid-connected and islanded microgrids with enhanced stability using nonlinear microgrid stabilizer," IEEE Trans. Smart Grid, vol. 3, no. 3, pp. 1291- 1301, Sep. 2012.
[17] X. Chen, W. Pei, and X. Tang, "Transient stability analysis of micro-grids with multiple distributed generations," in proc. IEEE Power Syst. Tech. Conference (POWERCON), Oct. 2010, pp. 1-8.
[18] M. E. Baran, and I. El-Markaby, "Fault analysis on distributed feeders with distributed generators," IEEE Trans. Power Syst., vol. 20, no. 4, Nov. 2005.
[19] R. Lasseter, "Integration of Distributed Energy Resources: The CERTS microgrid concept," CERT Rep., Apr. 2002.
[20] S. R. Wall, "Performance of inverter interfaced distributed generation," in IEEE/PES Trans. and Dist. Con. Exposition, Oct. 2001, pp. 945–950.
[21] J. Keller, and B. Kroposki, "Understanding fault characteristics of inverter-based distributed energy resources," Tech. Rep. NREL/TP-550- 46698, National Renewable Energy Laboratory, Jan. 2010.
[22] Radial Test Feeders—IEEE Distribution System Analysis Subcommittee. [Online]. Available: http://ewh.ieee.org/soc/pes/dsacom/testfeeders.html
[23] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuña, and M. Castilla, "Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization," IEEE Trans. Ind. Electron., vol. 60, no. 4, pp. 158–172, Jan. 2011.
[24] Zadeh, A., "Fuzzy sets," Inf. Control, Vol. 8, pp. 338-353, 1965.
[25] Bevrani, H., and Hiyama, T., Intelligent Automatic Generation Control. New York: CRC, Apr. 2011.